N° d'Enregistrement
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ARTICLE PRINCIPAL

Recouvrant en partie

LA THESE DE DOCTORAT ES SCIENCES MATHEMATIQUES

présentée

A L'UNIVERSITE PARIS VI

par

Michel CREZE

pour obtenir

le grade de Docteur Es-Sciences

Sujet de la Thèse : "Rotation différentielle de la Galaxie et cinématique des objets de Population I ; analyse de la qualité des données et des méthodes statistiques utilisées.

Soutenue le 27 juin 1972, devant la Commission d'Examen composée de :

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On the Possible Existence of Different Interstellar Extinction Laws in the Spiral Arms and in the Field Regions

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Summary. The ratio $\mathscr{R}$ of total to selective extinction is derived from a comparison of spectroscopic and photometric data with the kinematical parallaxes computed from radial velocities, through a model of galactic differential rotation. H II regions, Population I Cepheids and Open Clusters are used for this purpose.
$\mathscr{R}$ is shown to depend on both galactic longitude and color excess. The galactic longitude variation appears to be strongly correlated with the local spiral structure and the dependence on color excess confirms the correlation observed by Fernie and Marlborough (1963). Both these phenomena can be explained if the interstellar extinction law is different in and outside the galactic spiral arms. This difference may result either from a different chemical composition or from a different size distribution of the interstellar grains. $\mathscr{R}$ should vary from about 1.5 to about 4.0 according as the part of the line of sight lying inside the spiral arms is near zero or very large (about 2 kpc).

Key words: interstellar extinction – spiral structure – kinematical parallaxes

I. Introduction

Previous investigations on the use of stellar parallaxes in determining the parameters of galactic differential rotation (Crézé, 1970a and b) have led us to look for the information about interstellar extinction which can be derived from kinematical data.
A method is proposed for deriving the ratio

$$\mathscr{R} = A_V / E\,(B-V) \tag{1}$$

of total to selective absorption. These methods are based on the comparison between kinematical parallaxes deduced from the radial velocities and the spectroscopic and photometric data.
Three samples of Population I objects have been used for this purpose, because they have small velocity ellipsoids: Population I Cepheids, Open Clusters and H II regions. The samples are used for checking the existence of variations of $\mathscr{R}$ which have been observed by various authors.

II. Previous Results

The ratio $\mathscr{R}$ has formed the subject of a number of studies using photometric methods. The constant value $\mathscr{R} = 3$ is usually adopted. A discussion of this value is given by Sharpless (1963). Some authors however have suggested that this result is questionable. After Wampler (1961), Fernie and Marlborough (1963) show $\mathscr{R}$ to vary with the galactic longitude $\mathscr{R}$. Furthermore they pointed out a correlation between $\mathscr{R}$ and the color excess $E\,(B-V)$: from their data, they derived the relation (2)

$$\mathscr{R} = 2.31 + 0.84\,E\,(B-V) \pm 0.19 \pm 0.24 \tag{2}$$

Johnson (1968) gives a variation of $\mathscr{R}$ with the galactic longitude which is not at all the same as the one found by Fernie and Marlborough. His result has often been questioned, but most authors agree with him about the existence of a local anomaly of the interstellar extinction in the direction of the Orion Nebula.
Isobe (1968) calculates $\mathscr{R}$ in various ranges of galactic longitude from an extensive set of observations, he gives $\mathscr{R} = 3$ with variations smaller than 0.1 and a standard error about ± 0.1. But the distribution of his sample over galactic longitudes leaves some large regions without measurements. Lastly, the methods for deriving $\mathscr{R}$ from photometric data alone may be questioned, either because the shape of the absorption law remains somewhat uncertain in the infrared region, or because the estimations are based on differential extinction inside Clusters or Associations and do not take into account the extinction along the whole line of sight.
Thus we felt it worth comparing this set of results with other estimates, even lacking in accuracy, but quite independent. The comparison between spectroscopical or photometric distance moduli which include interstellar reddening, with kinematical parallaxes de-

duced from the radial velocities through a model of galactic rotation, provides estimates of the total interstellar absorption and does not depend on any hypothesis about the shape of the reddening curve.

III. Principle of the Method

Using the notations defined in a previous paper (Crézé, 1970b), the radial velocity of one star at the distance R from the galactic center, can be written (3) after correction of the solar Motion.

$$V_R = -2A\,(R-R_0)\sin l\cos b \qquad (3)$$
$$-2\alpha\,(R-R_0)^2\sin l\cos b + V_\varepsilon\,.$$

The second order term of the galactic differential rotation is very small and can be corrected using an approximate value of the distance. So we can reduce the expansion of the radial velocity to the simpler form:

$$V_R = -2A\,(R-R_0)\sin l\cos b + V_\varepsilon \qquad (4)$$

including some information about the distance R, and the peculiar velocity of the star: V_ε which can be considered as normally distributed with zero mean.

$$r = \exp 0.2 \ln 10\,[(m-M)+5-\mathscr{R}\,E\,(B-V)]\,, \qquad (5)$$

$$R^2 = r^2\cos^2 b + R_0^2 - 2r\,R_0\cos l\cos b\,. \qquad (6)$$

An estimation of the galactocentric distance R is derived from (4), and the kinematical distance modulus is deduced from R through (6) and (5). The difference between this value and the reddened distance modulus computed from spectroscopical and photometrical data provide an estimate of the total interstellar absorption A_v. Thus, given the color excess, we get an estimate of the ratio $\mathscr{R}$ (1). Of course, an estimate from only one star is not accurate at all, furthermore the errors are neither normally, nor symetrically distributed.

However, the derivation of $\mathscr{R}$ from V_R does not disturb the median of the distribution. This property may be used for estimating $\mathscr{R}$. The probabilities that the errors of the individual $\mathscr{R}$ will be either positive or negative are both 0.5 and the distribution of the values below and above the true one is binomial with parameter $p = 0.5$.

Thus n being the size the sample and the individual estimates of $\mathscr{R}$ being set in increasing order, the $\left(\frac{n+1}{2}\right)^{\text{th}}$ value is an unbiased estimate of $\mathscr{R}$. The confidence interval 68% (equivalent to a standard error) lies between the

$$\left(\frac{n+1}{2} - 0.5\sqrt{n}\right)^{\text{th}} \text{ and } \left(\frac{n+1}{2} + 0.5\sqrt{n}\right)^{\text{th}} \qquad (7)$$

values. The skewness of the distribution causes the assymetry of the error ranges in Figs. (1a) and (2).

It follows from (7) that the accuracy of the method does not necessarily increase with the size of the sample, it depends on whether a number of points are concentrated near by the central value. According to (1) and (4), such a concentration cannot exist:

– In a small sample with large V_ε, which is the case for the Open Clusters.
– If $\sin l$ is near zero for a number of stars (Fig. 1a).
– If there is a lot of small color excesses (Fig. 2).

IV. Characteristics of the Data Used

For each sample, the radial velocities, distance moduli and color excesses are needed. Such data are available for Population I Cepheids, H II regions, and Open clusters. The characteristics of these samples are summarized in Table 1. σ_U, σ_V, and σ_W are the standard deviations of the peculiar velocities.

Table 1. Characteristics of the samples

	Cepheids	OC (1)	OC (2)	H II Regions
Size of the sample	111	74	74	72
Distance moduli data				
Method of determination	PL	A0 or HR	A0	HR
Standard error of absolute Mag	0.20	0.30	0.10	0.50
Homogeneity of the data	+	–	+	–
Radial velocities data				
Standard deviations of the peculiar velocities				
σ_U (kms^{-1})	12	15	15	
σ_V (kms^{-1})	10	12	12	2–8
σ_W (kms^{-1})	6	6	6	
Homogeneity of the data	+	–	–	+

PL: Period/Luminosity relation of Cepheids.
A0: Fit of the Cluster's HR diagram to the Zero Age Main Sequence.
HR: From the Spectral Types and Luminosity Classes, using the calibration of Blaauw (1963).

a) Open Clusters

Studies of the galactic rotation from Open Clusters have been performed by Johnson and Svolopoulos (1961) and Crampton (1968). The sample of Johnson includes 36 clusters, the one of Crampton 63 clusters, but the last author gives no information about his sources. The catalog of Alter *et al.* (1970) has been used for getting a sample as large as possible. Data published since 1969 have been taken from various

sources for the following clusters: Tr 24 (OCI 999), NGC 6193, NGC 2175 from Kennedy (1971) Bok's galactic cluster from Jones (1969) Cr 399 (OCI 113) from Hall and Van Lowdingham (1970) NGC 7243 (OCI 221) from Hill and Barnes (1971).

Owing to the diversity of the sources (the catalog of Alter is a compilation), these data may not be expected to form an homogeneous set, either for the distances or for the radial velocities.

A new catalog of cluster distances has been published by Becker and Fenkart (1971). This set of values is homogeneous and accurate. Distances are available for about all the clusters with radial velocity.

In the following, the sample of clusters taken from Alter's catalog will be designated by OC (1) and the same sample with distances from Becker by OC (2). Since both the samples have the same radial velocities, the results from one or the other are clearly not independent. σ_U, σ_V, σ_W are kept from Delhaye (1965).

b) H II *Regions*

These have been studied by Georgelin and Georgelin (1970b) who published a catalog including the radial velocities of the regions and the Spectroscopic and photometric data for the exciting stars. (Georgelin and Georgelin, 1970a).

The radial velocities are accurate and homogeneous. The H II regions show little deviation from the general velocity field: the standard deviation of the peculiar velocities ranges between 2 and 8 kms^{-1} according to the same authors (1970b), below 7 kms^{-1} according to Mezger and Höglund (1967).

The distances of the exciting stars have been derived from the spectral types and luminosity classes using the calibration of Blaauw (1963). The dispersion of the absolute magnitudes obtained this way is at least 0.5 magnitudes (according to Jung, 1969).

c) Cepheids

The data are the ones of Kraft and Schmidt (1963), and have formed the subject of a separate work (Crézé, 1970b).

V. Results

The method described above has been applied to a sample including 111 Cepheids and 72 H II regions. Table 2 gives the results derived from the whole sample according to the adopted A and R_0. The influence of R_0 can clearly be neglected, while that of A is weak. All the results are compatible with $\mathscr{R} = 3$, provided that A does not reach 17 kms^{-1} kpc^{-1}. Table 3 shows the influence of the other adopted parameters, one can see that only a large error in V_0 can change the results.

Table 2. Estimation of $\mathscr{R}$ from the whole sample, for various adopted A and R_0

A (kms^{-1} kpc^{-1})	15	16	17
R_0 (kpc)			
8	2.94	3.21	3.36
9	2.95	3.16	3.37
10	2.92	3.11	3.30

Table 3. Errors on $\mathscr{R}$ resulting from the errors on the adopted components of the Solar Motion and the second order term of the galactic differential rotation α

Parameter	U_0 (kms^{-1})	V_0 (kms^{-1})	W_0 (kms^{-1})	α (kms^{-1} kpc^{-2})
Adopted value	9	15	7	0.8
Error on the adopted value	+3	+3	+3	+0.3
Error resulting on $\mathscr{R}$	+0.07	+0.30	+0.00	+0.06

The same computation has been performed for parts of the sample divided according to either galactic longitudes a (or the color excesses b).

a) The longitude intervals are 45° long, the origin of the first interval being either 0° or 22°.5 (Fig. 1a). Thus it can be seen that the choice of one peculiar origin has no influence over the results. Any change in A causes a slight translation of the whole curve along the Y-axis, but no modification in its shape.

A variation of $\mathscr{R}$ with l^{II} appears in Fig. 1a, it shows no clear resemblance to the ones observed by Fernie and Marlborough (1963) or by Johnson (1968). The curve 1b shows the variation of the thickness of the local galactic arm calculated for each l^{II}, using the approximate model of Fig. 3, according to the indications of MacCuskey (1970) and the observations of Becker and Fenkart (1970). A possible connection appears between this curve and the observational points 1a.

b) The median values of $\mathscr{R}$ for three ranges of the parameter $E(B-V)$ are plotted in Fig. 2. The straight line is the result of Fernie and Marlborough (Eq. 2) the agreement with our points is fairly good. The fit of a linear relation to our points, by least squares, provides equation (11) if $A = 15$ and $R_0 = 10$ kpc, or equation (12) if $A = 16$ and $R_0 = 9$.

$$\mathscr{R} = 2.26 + 1.10\ E(B-V), \tag{8}$$

$$\mathscr{R} = 2.59 + 0.90\ E(B-V) \pm 0.40 \pm 0.40\,. \tag{9}$$

The color excesses averaged over each longitude interval are plotted in Fig. 1c, so as to check that no correlation exists with the variation observed with the galactic longitude.

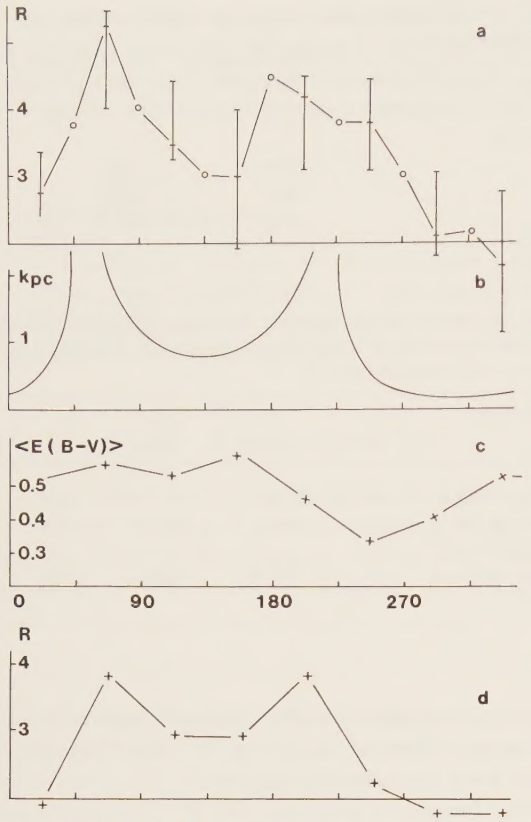

Fig. 1a-d. Variation of $\mathscr{R} = A_v/E\ (B-V)$ with galactic longitude. a Estimated median points from Cepheids and H II regions. The origin of the first interval is either 0°: + ; or 22°5: ○. b Thickness of the local spiral arm. c Color excesses averaged over each longitude range. d Median points derived from the model $\mathscr{R} = 1.44 + 1.5\,\varrho$

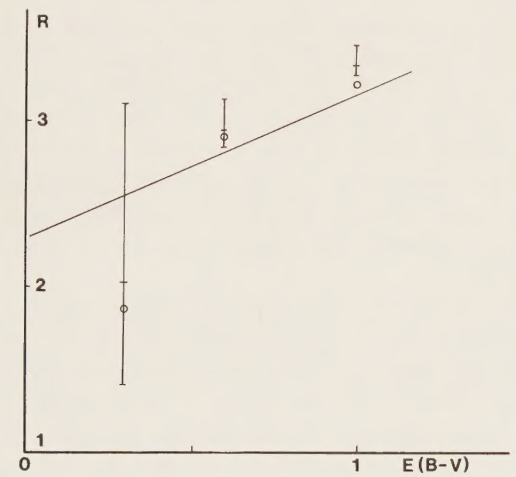

Fig. 2. Variation of $\mathscr{R}$ with the color excesses. + estimated median points from Cepheids and H II regions. ○ median points derived from the model: $\mathscr{R} = 1.44 + 1.5\,\varrho$

The main features of the spiral arms within 4 kpc are illustrated in Fig. 3. The frequency of large color excesses appears to be significantly higher inside the spiral arms. It suggests that the dependences on color excesses and galactic longitudes may yet have a common cause.

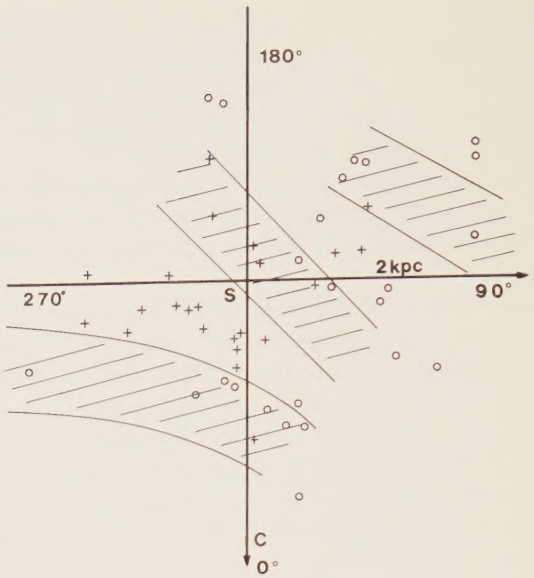

Fig. 3. Positions of the large color excess $(E\,(B-V) \geqq 1.)$: ○, and of the small color excesses $(0.2 \leqq E\,(B-V) \leqq 0.3)$: +, with respect to the spiral arms within 4 kpc: hatched regions

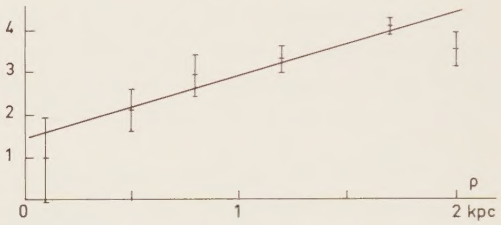

Fig. 4. Variation of $\mathscr{R}$ with the total thickness ϱ of spiral arms over the line of sight (estimated median points)

From the spiral pattern of Fig. 3, the total length of the line of sight which lies inside the spiral arms can be computed for any object. Let ϱ be this length. The median values of $\mathscr{R}$ are then derived from parts of the sample divided according to the new parameter ϱ (Fig. 4). $\mathscr{R}$ is clearly seen to increase with ϱ. This dependence may indicate that the absorption law is different in and outside the spiral arms, i.e. that the interstellar grains may have a different chemical composition or a different size distribution.

The equation of the straight line fitted in Fig. 4 is (10); there is no evidence for a linear relation,

$$\mathscr{R} = 1.44 + 1.5\,\varrho \qquad (10)$$

equation (13) provides only a convenient approximation for calculating $\mathscr{R}$ for any individual star. By means of this relation, medians of $\mathscr{R}$ have been computed in the various l^{II} and $E\,(B-V)$ ranges. The results are plotted on Figs. 1d and 2 for comparison with the observational points. The agreement is fairly good, though the values derived from the model appear to be a little under-estimated.

The objection may be raised that Eq. (10) is really just a result of Eq. (8): the frequency of large color excesses

is larger in the spiral arms because the interstellar dust is concentrated in the arms, and $\mathscr{R}$ depending on color excess is larger in the corresponding regions. Such an explanation cannot be retained, indeed, if only the concentration of the interstellar dust varies, the color excesses must also vary, but the constant $\mathscr{R}$ does not [the variations pointed out by Blanco and Lennon (1961) are negligeable with respect to Eq. (8)].
Moreover the dependence of $\mathscr{R}$ on the total thickness of spiral arms provides explanations of both the dependences on color excess and galactic longitude. This second one cannot be understood otherwise, owing to the fact that large values of $\mathscr{R}$ are derived in the directions corresponding to the local spiral arm where the color excesses are not particularly large.
Important variations of $\mathscr{R}$ must be directly related to the shape of the interstellar extinction law and this law depends on the size distribution, shape and chemical composition of the interstellar grains (Greenberg, 1968).

Thus the observed phenomena suggest that different interstellar grains (or different size distributions of the grains) are encountered inside and outside the spiral arms.

VI. Conclusions

The comparison of kinematical parallaxes with spectroscopic and photometric data provides a statistical estimation of the total interstellar extinction. Such estimations have been made using the radial velocities of Cepheids, H II regions and Open Clusters. If only one value of the ratio $\mathscr{R}$ is derived, the results do not deviate significantly from the classical value $\mathscr{R}=3$. But the results of differential determinations show a dependence of $\mathscr{R}$ on both galactic longitudes and color excesses.
Both these phenomena can be explained if the interstellar extinction law is different in and outside the galactic spiral arms. $\mathscr{R}$ should vary from about 1.5 if no "spiral arm" dust is encountered over the line of sight, to about 4 if a large part of the line of sight lies inside the spiral arms.
If such an inhomogeneity of the absorption is confirmed, the distances of objects at low galactic latitudes will change significantly. The consequences of such a modification on the galactic rotation have been studied and form the subject of a separate paper (Crézé, 1972).

Ce travail est l'article principal de la thèse que M. Crézé a soutenue à l'Université de Paris VI le 27 Juin 1972, en vue d'obtenir le diplôme de Docteur ès sciences mathématiques, devant un jury composé de MM Rösch Président, Blaauw, Delhaye, Lévy examinateurs. N° CNRS AO 7118.

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